Coherent Effects in Microwave Backscattering Models for Forest Canopies

Sasan S. Saatchi and Kyle C. McDonald
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, California 91109, U.S.A.
T: 818-354-1051; F: 818-393-6943; EMAIL.: saatchi@bacchus.jpl.nasa.gov

ABSTRACT

In modeling forest canopies, several scattering mechanisms are taken into account: 1)volume scattering, 2)surface-volume interaction, and 3) surface scattering from forest floor. Depending on the structural and dielectric characteristics of forest canopies, the relative contribution of each mechanism in the total backscatter signal of an imaging radar can vary. In this paper, two commonly used first order discrete scattering models, Distorted Born Approximation (DBA) and Radiative Transfer (RT) are used to simulate the backscattered power received by polarimetric radars at P-, L-, and C-bands over coniferous and deciduous forests. The difference between the two models resides on the coherent effect in the surface-volume interaction terms. To demonstrate this point, the models are first compared based on their underlying theoretical assumptions and then according to simulation results over coniferous and deciduous forests. It is shown that by using the same scattering functions for various components of trees (i.e. leaf, branch, stem) the radiative transfer and distorted Born models are equivalent, except in low frequencies where surface-volume interaction terms become important and the coherent contribution is significant. In this case, the difference between the two models can reach up to 3 dB in both co-polarized and cross-polarized channels which can influence the performance of retrieval algorithms based on the RT models.

1. INTRODUCTION

On a global scale, forest ecosystems, representing approximately 90 Percent of the standing biomass, play an important role in the hydrologic and biogiochemical cycles of the earth system. Monitoring natural and antropogenic changes continuously occurring in forests can have a major impact in understanding the status of carbon dioxide and moisture exchanges between the earth boundary and atmosphere. Without any doubts, remote sensing techniques have the potential of monitoring forest canopies and possibly inferring climatologically or hydrologically important parameters. However, interpretation of the remotely sensed information is not often straightforward since it involves a series of efforts such as understanding the measured and processed signal, developing an appropriate theoretical model of the forest canopy, and finally estimating forest parameters. In recent years, attention has been given to microwave remote sensing as a promising tool mainly because of its high resolution, all weather information capability, penetration into the forest canopy, and sensitivity to vegetation geometry and moisture. The results from controlled experiments and from airborne and spaceborne SAR instruments (e.g. JPL/NASA AIRSAR, ERS-1, and JERS- 1) have contributed to developing this notion [1]-[4].

One of the major obstacles in interpreting the radar image data is in understanding the interaction of the radar signal and the forest canopy within a resolution cell through different backscattering mechanisms. For this reason, various phenomenological and theoretical models have been developed to simulate the measured backscatter signal. In developing radar backscatter models for forest canopies two objectives are often considered: 1) how well the model simulates the SAR data and 2) how easily and accurately the model can be inverted to estimate forest canopy parameters (e.g. biomass, water content, structural parameters). So far, majority of mathematical models for forest canopies are developed by satisfying the first objective [5]-[7].

Two microwave backscatter models, distorted Born approximation (DBA) and radiative transfer (RT) are widely used to simulate the radar returns from forests. These models fall into the general categories of wave approach and energy approach. The DBA model is based on the wave theory and it is considered more appropriate when the incidence wavelength is long and the coherent backscattering resulting from surface-volume interaction terms is important, The RT model is based on the energy approach and it is more appropriate in shorter wavelengths when the coherent backscattering is small due to the attenuation from branches and leaves. However, both models have been used extensively to simulate forest backscatter at wavelengths from 60 cm (P-band) to 3 cm (X-band) [5] -[12]. These models have become progressive y more complicated during the past few years and they have been verified against radar measurements over vegetated surfaces such as grasslands, crops, and forests.

The primary objective for comparing these two forest backscatter models is to address the following questions: 1) how do the relative backscatter contributions from tree components (branch, needle and leaves, and trunk) appear in each model?, 2) How do the models behave across the SAR frequency range (P-band, L-band, and C-band)?, and 3) What is the relative importance of the coherent contribution? In studying the radar data acquired over the boreal forest of Canada, we observed the strong contribution of trunk-ground interaction at P-band and L-band over a jack pine canopy [30]. This scattering interaction carries information about the coherent effect. By addressing the above questions, we will be able to understand the applicability of backscatter models in interpreting radar images over forest canopies.

The paper is organized by first paramterizing a forest canopy for microwave remote sensing applications in section 2. In section 3, the mathematical formulation of distorted Born approximation and the radiative transfer models for a two layer canopy are presented and discussed. In section 4, the models are compared analytical y and in section 5, the model simulations are compared for coniferous and deciduous forests. The results of simulations and the relative contribution of scattering mechanisms are discussed and summarized in sections 6 and 7 respectively.

2. PARAMETRIZATION OF FOREST CANOPIES

A forest canopy model for microwave remote sensing application has two main characteristics: 1) the general form of the scattering or radiating medium, and 2) the electromagnetic geometry and properties of vegetation components. In the range of microwave frequencies considered for SAR applications (400 MHz to 10 GHz), the forest canopy is often represented by a discrete random medium (i.e. an ensemble of leaves, branches, and trunks). An alternative approach can be a continuous random medium where the vegetation layer is replaced by a randomly fluctuating dielectric permittivity. The discrete approach has conceptual and theoretical advantages over the continuous approach because on the one hand, it is a more realistic representation of the canopy, and on the other hand, the radiative sources present in the measured backscatter signal can be traced to the canopy components directly [13].

In this study, we characterize the forest canopy as a discrete random medium consisting of two layers of vegetation over a rough ground surface. Figure 1 shows a typical two layer discrete model where canopy constituents are separated into individual scatterers. The two layer model is often used for deciduous trees and in conifers where a clear boundary between the crown and trunk layers can be identified. The model also allows for cases where the tree trunks are extended into the crown layer. It is assumed that the crown layer consists of randomly distributed branches and leaves and has an equivalent thickness of d_c and the trunk layer consists of vertically distributed tree trunks and has an equivalent height of d_t. Throughout the paper we use the term “forest canopy” to address standing trees (crown and trunk layers).

The canopy components are considered the scattering elements in the forest model and they are modeled by lossy dielectric canonical geometries such as discs and circular cylinders. These elements are defined by their size, angular distributions, density, and the dielectric constant that are provided from available *in situ* measurements. The dielectric scatterers are distributed with a prescribed orientation to mimic the canopy geometry as closely as possible. For simplicity, we assume that the scatterers are distributed uniformly in the azimuthal coordinate, have fixed sizes, and their dielectric constant does not change with size and location. Scattering from individual scatterers are obtained by using appropriate approximations in terms of the operational wavelength. The underlying ground is modeled as a homogeneous half space with dielectric constant of ε_g. The soil rough interface is characterized by its *rms* height.

3. MODEL FORMULATION

Using the discrete scattering approach, backscattering expressions are derived based on the aggregation of electromagnetic wave or energy scattered from discrete scatterers in a random medium, Mathematical formulation of the problem leads to integral equations for the scattered field (wave approach) or intensity (energy approach) in terms of the scattering properties and statistical characteristics of individual scatterers. These equations, being of stochastic nature, are difficult to solve exactly and therefore, approximate solutions are obtained by using perturbation theory. The perturbation series are generated based on the existence of a small parameter such as density of scatterers in the medium (sparse medium) and the single scattering albedo. The series is then truncated by some closure approach which limits the number of multiple scattering effects in the medium. In addition, since the size of scatterers are often comparable to the wavelength of incoming radiation, other factors such as diffraction may also have an impact on the implementation of the perturbation theory.

A two layer forest canopy model requires formulation of the dominant scattering mechanism within the canopy. These dominant mechanisms are 1) crown volume scattering, 2) crown-ground interaction, 3) trunk-ground interaction, and 4) ground scattering, The scattering mechanisms are illustrated in Fig. 2. Other scattering events which include double scattering from ground or volume scattering from trunk are considered small and therefore not included in the formulation [7],[8]. We start the problem formulation by using the wave theory approach and applying the distorted Born approximation (DBA) to obtain the backscattering coefficients [9],[14]. The first order radiative transfer theory is then formulated following the expressions given by [15].

3.1 *Distorted **Born** Approximation*

The distorted Born approximation is a first order scattering theory. The scattered field from the canopy is found by first assuming that the wave incident on each scatterer is the mean field in the layer and then by embedding the scatterers in the equivalent (mean) medium and computing the scattered field. In mathematical terms, the mean field is obtained by iterating the self consistent multiple scattering equations using the Foldy-Lax approximation which is valid in the limit of small fractional volume [16]. The solution of the mean field suggests that the medium can be replaced by an effective dielectric constant. The use of the equivalent medium instead of the original background medium (air) implies that both the incident and scattered waves attenuate while propagating in the medium, Solving the scattered field from scatterers embedded in the equivalent medium results in solving the multiple scattering equations again by iteration in the limit of the first order Born approximation which is valid when the scatterers have small albedo(ratio of scattering cross section over total cross section). For plant canopies, this assumption can hold for frequencies less than 10 GHz [13]. The backscttering coefficient from the medium is then obtained by computing the correlation of the scattered fields. Recently, the DBA has been used to model forest canopies in one layer [9], [17]. Here, new expressions are given for a two la yer forest canopy.

For a two layer forest canopy, consisting of upright trunks, crown layer, and the forest floor, the backscattering coefficient can be decomposed in the following fashion:

$$\sigma^0_{pq} = \sigma^0_{pqc} + \sigma^0_{pqcg} + \sigma^0_{pqtg} + \sigma^0_{pqs} \tag{3.1.1}$$

where the subscripts c, cg, tg, and s denote the crown volume scattering, crown-ground interaction, trunk-ground interaction, and surface scattering respectively. Here, q and p, being either horizontal (h) or veritical (v), represent the polarizations of the incidence and scattered fields respective y. The terms in equation (1) can be expressed as:

Crown volume scattering:

$$\sigma^0_{pqc} = (\rho_l \sigma_{ld} + \rho_b \sigma_{bd})\left[\frac{1 - e^{-2Im(K_{pc}+K_{qc})d_c}}{2Im(K_{pc} + K_{qc})}\right] \quad (3.1.2)$$

Crown-ground double bounce scattering:

$$\begin{aligned}\sigma^0_{pqcg} &= (\rho_l \sigma_{ldr1} + \rho_b \sigma_{bdr1})\left|\Gamma_p\right|^2\left[\frac{1 - e^{-2Im(K_{qc}-K_{pc})d_c}}{2Im(K_{qc} - K_{pc})}\right] \\ &+ (\rho_l \sigma_{ldr2} + \rho_b \sigma_{bdr2})\left|\Gamma_q\right|^2\left[\frac{1 - e^{-2Im(K_{pc}-K_{qc})d_c}}{2Im(K_{pc} - K_{qc})}\right] \\ &+ 2Re\left\{(\rho_l \sigma_{ldr12} + \rho_b \sigma_{bdr12})(\Gamma_p \Gamma_q^*)\left[\frac{1 - e^{-2iRe(K_{pc}-K_{qc})d_c}}{2iRe(K_{pc} - K_{qc})}\right]\right\}\end{aligned} \quad (3.1.3)$$

Trunk-ground double bounce Scattering:

$$\begin{aligned}\sigma^0_{pqtg} &= \rho_t \sigma_{tdr1}\left|\Gamma_p\right|^2\left[\frac{1 - e^{-2Im(K_{qt}-K_{pt})d_t}}{2Im(K_{qt} - K_{pt})}\right]\beta_t \\ &+ \rho_t \sigma_{tdr2}\left|\Gamma_q\right|^2\left[\frac{1 - e^{-2Im(K_{pt}-K_{qt})d_t}}{2Im(K_{pt} - K_{qt})}\right]\beta_t \\ &+ 2Re\left\{\rho_t \sigma_{tdr12}(\Gamma_p \Gamma_q^*)\left[\frac{1 - e^{-2iRe(K_{pt}-K_{qt})d_t}}{2iRe(K_{pt} - K_{qt})}\right]\gamma_t\right\}\end{aligned} \quad (3.1.4)$$

Surface Scattering:

$$\sigma^0_{pqs} = \sigma^0_{pqg}\, e^{-2Im\left[(K_{pc}+K_{qc})d_c + (K_{pt}+K_{qt})d_t\right]} \quad (3.1.5)$$

where

symmetry of the scatterers in the medium, the propagation constants are either horizontally or vertically polarized.

In above expressions, the scattering amplitudes of leaves (or needles) are obtained by using the quasi-static method which is valid when the sizes of the scatterers are small compared to the wavelength [18], [19]. For branches and trunks the physical optics approximation is used which is valid when the radius of cylinder is small compared to its length and when the resonant interaction between the two ends do not occur[20]. The angular distribution of the needles, branches and mmks are approximated by analytical functions which are representative of canopies under consideration.

The last quantities that remain to be identified are the surface scattering contributions. In equations (3.1.3) and (3.1.4), the surface contribution appears in terms of the surface reflectivity reduced by the attenuation of the incoming and scattered waves and influenced by the surface roughness parameter which in turn is determined by the Kirchhoff's approximation [21]. The surface reflectivity is given by

$$|\Gamma_p|^2 = r_g |R_p|^2 e^{-4Im(K_{pc}d_c + K_{pt}d_t)} \tag{3.1.9}$$

where $r_g = \exp(-4k_0^2 s^2 \cos^2\theta_0)$ is the roughness effect and $|R_p|^2$ is the Fresnel reflectivity for polarization p. The parameter s is the surface *rms* height. The backscattering coefficient from the rough surface in equation (3.1.5) is obtained by employing a semi-empirical method developed by Oh at al. [21].

3.2 Radiative Transfer

Radiative transfer theory deals with the transport of energy through a medium containing particles that absorb, emit and scatter radiation [22] -[2.4]. The development of the theory is heuristic. However, there have been many studies to derive the radiative transfer theory from wave theory approach [22]. In formulating the radiative transfer equations for an ensemble of particles, the diffraction effects are not taken into consideration, and unlike the wave theory it assumes that there is no correlation between the fields, and therefore the addition of power, rather than the addition of fields holds. To include the polarization information of radiation, the vector RT equation is formulated in terms of the vector specific intensity **I(r,p)**, where r is the position vector and p is the direction of propagation. In solving the vector RT equation in a vegetation canopy, an expression is sought that relates the vector specific intensity Ii incident on the canopy to that which is scattered from the canopy I^s. This is achieved through a 4x4